CORRELATION OF AGN JET POWER WITH THE ENTROPY PROFILE IN COOLING FLOW CLUSTERS

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ABSTRACT

We find that the power of jets that inflate bubble pairs in cooling flow clusters of galaxies correlates with the size r_α of the inner region where the entropy profile is flat, as well as with the gas mass in that region and the entropy floor−the entropy value at the center of the cluster. These correlations strengthen the cold feedback mechanism that is thought to operate in cooling flow clusters and during galaxy formation. In the cold feedback mechanism the central super-massive black hole (SMBH) is fed with cold clumps that originate in an extended region of the cooling flow volume, in particular from the inner region that has a flat entropy profile. Such a process ensures a tight feedback between radiative cooling and heating by the SMBH (the AGN). For a SMBH accretion efficiency (of converting mass to energy) of $\eta_j = 0.1$, we find the accretion rate to be $\dot{M}_{\rm acc} \simeq 0.03(r_\alpha/10 \text{ kpc})^{1.7} M_\odot \text{ yr}^{-1}$. This expression, as well as those for the gas mass and the entropy floor, although being crude, should be used instead of the Bondi accretion rate when studying AGN feedback. We find that the mass of molecular gas also correlates with the entropy profile parameters r_α and M_g, despite that the jet power does not correlate with the molecular gas mass. This further suggests that the entropy profile is a fundamental parameter determining cooling and feedback in cooling flow clusters.

1. INTRODUCTION

It is now clear that in many clusters of galaxies moderate quantities of the intra-cluster medium (ICM) are cooling to low temperatures ($T \ll 10^5$ K; see reviews by Peterson & Fabian 2006 and McNamara & Nulsen 2007). *Moderate* implies here that the mass cooling rate to low temperatures is much lower than the cooling rate expected without heating, but it is much larger than the accretion rate onto the supermassive black hole (SMBH) at the center of the cluster. The cooling mass is either forming stars (e.g., O'Dea et al. 2008; Rafferty et al. 2008), forming cold clouds (e.g., Edge et al. 2010), accreted by the SMBH, or is expelled back to the ICM and heated

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when it is shocked. In this *moderate cooling flow model* (Soker et al. 2001; Soker & David 2003; Soker 2004), the SMBH is fed by cold clumps originating in an extended region ($r \sim 5 - 30$ kpc) of the cooling flow, in a process termed the *cold feedback mechanism* (Pizzolato & Soker 2005; Soker 2006; Pizzolato 2007; Pizzolato & Soker 2010). The cold feedback mechanism overcomes some severe problems encountered by feedback models that are based on accreting gas directly from the hot phase (Soker 2006; Soker et al. 2009; Pizzolato & Soker 2010), such as the problems in the Bondi accretion (McNamara et al. 2010). The cold feedback mechanism is compatible with observations that show that heating cannot completely offset cooling (e.g., Wise et al. 2004; McNamara et al. 2004; Clarke et al. 2004; Hicks & Mushotzky 2005; Bregman et al. 2006; Salome et al. 2008; Wilman et al. 2009; Peterson & Fabian 2006), and preliminary steps are taken to include it in feedback simulations (Gaspari et al. 2010).

The properties and behavior of the clumps that cool to low temperatures were studied by us in previous papers (Pizzolato & Soker 2005; Soker 2006; Pizzolato 2007; Pizzolato & Soker 2010). The distribution of cold clumps is complicated, and there is no way for us to determine it. For that, in this paper we use our recent results Pizzolato & Soker (2010) that are summarized in section 2, to derive in section 3 a semi-empirical phenomenological expressions for the accretion rate onto the SMBH. The main result of Pizzolato & Soker (2010) and the previous papers is the sensitivity of cold clump evolution to the entropy profile. Readers interested only in the phenomenological formulae for accretion can skip section 2 and go directly to section 3. Our short summary is in section 4.

2.   BASIC PROPERTIES OF COOLING CLUMPS

The cold feedback mechanism assumes that the ICM is populated by a widespread assembly of cold clumps. We define the clump's density contrast

$$\delta = (\rho' - \rho)/\rho, \tag{1}$$

where ρ' is the mass density of the clump, and ρ is the mass density of the surrounding ICM.

As shown in Pizzolato & Soker (2005, 2010) the fate of a clump critically depends on its initial overdensity. (*i*) *Stable clumps.* They start with a small initial overdensity, and they are eventually stabilised. (*ii*) *Relatively unstable clumps.* Moderately dense clumps, whose density contrast decreases as they fall in, but they manage to reach the center. (*iii*) *Absolutely unstable clumps.* These have $\delta > \delta_C$, and their density increase monotonically.

The critical density is given by Pizzolato & Soker (2010)

$$[\omega(\delta_C, T)]^{-2} \delta_C = \chi, \tag{2}$$

where

$$\omega(\delta, T) = \frac{(1+\delta)^2}{\Lambda(T)} \Lambda\left(\frac{T}{1+\delta}\right) - 1, \tag{3}$$

depends on δ and the ICM temperature T through the cooling function Λ. The left hand side of equation (2) is an implicit function of δ_C, while the right hand side depends on the ICM properties and the radius of the clump according to

$$\chi = \frac{3}{8} \, C_D \, \frac{g/a}{\omega_{\rm BV}^4 \, \tau_{\rm cool}^2}, \tag{4}$$

where

$$\omega_{\rm BV}^2 = \frac{3}{5} \frac{g}{r} \frac{d \ln K}{d \ln r}, \tag{5}$$

is the Brunt–Väisälä frequency, $\tau_{\rm cool}$ is the ICM cooling time, a is the clump's radius (assumed spherical), g is the gravitational acceleration, K is the entropy, and $C_D \simeq 0.75$ is the drag coefficient (Kaiser 2003). A plot of δ_C as a function of χ for several values of T is shown in Fig. 1. Note that since $\chi \propto 1/a$, large clumps must be with a larger density contrast than small clumps to be unstable.

From equation (4) it is clear that the evolution of overdense, hence cooler, clumps is very sensitive to the cooling time and the entropy profile. Cooling of clumps is favored for a short cooling time and a flat entropy profile (by flat we refer to a moderate slope as well). The sensitivity of the clump evolution to the entropy profile is at heart of our present study.

We define the entropy logarithmic gradient

$$\alpha \equiv \frac{d \ln K}{d \ln r}, \tag{6}$$

According to Donahue et al. (2006) and Cavagnolo et al. (2009) in cooling flow clusters the entropy profile is flat, $\alpha \ll 1$, in the center, and it has $\alpha \simeq 1$ in the outer regions. As in previous papers we take $10 \lesssim a \lesssim 100$ pc. For $\delta_C = 1$ the condition for the clumps to be unstable is $\chi \gtrsim \chi_c \simeq 0.1$, where χ_c is the critical value of χ. Indeed, we define r_α to be the radius where $\alpha = 0.5$, and find that for our cluster sample $0.1 \lesssim \chi(r_\alpha) \lesssim 3$. This condition on χ translates to a condition on the cooling time, evaluated at $\sim r_\alpha$

$$\tau_{\rm cool} \lesssim 3 \times 10^8 \left(\frac{r}{10 \text{ kpc}} \right) \left(\frac{a}{0.01 r} \right)^{-1/2} \left[\frac{(gr)^{1/2}}{600 \text{ km s}^{-1}} \right]^{-1/2} \left(\frac{\alpha}{0.5} \right)^{-1} \chi_c^{-1/2} \text{ yr.} \tag{7}$$

It is interesting to note that Rafferty et al. (2008) found that in clusters where the cooling time at a radius of 12 kpc is $\tau_{\rm cool}(12 \text{ kpc}) < 8.5 \times 10^8$ yr $\equiv \tau_s$, high rate of star formation occurs. Equation (7) above gives a limit of $\sim 0.3 \tau_s$, but for clumps of size $a = 10^{-3} r$ ($a = 10$ pc at $r = 10$ kpc) it gives a time scale of $\tau_{\rm cool} \simeq \tau_s$. We conclude that a high cooling rate of over-dense clumps in the outer regions of the cooling flow, where $\alpha \simeq 0.5 - 1$, can occur, according to the cold feedback mechanism, when the cooling time is $\tau_{\rm cool}(10 \text{ kpc}) \lesssim 10^9$ yr, in agreement with observations of star formation (Rafferty et al. 2008).

In the inner regions where $\alpha \ll 1$, more clumps can cool. However, this region contains less mass than the outer regions, and it is more prone to AGN heating. Although there are much to

be done, the cold feedback mechanism can generally account for the limit of $\tau_s \simeq 10^9$ yr for a substantial star formation to occur, as found by Rafferty et al. (2008).

It is observed that major AGN activity occurs at a general time intervals of $\sim 10^8$ yr, (e.g., Wise et al. 2007 for Hydra A). In the cold feedback mechanism the time scale is determined mainly by regions from where large quantity of gas might be cooling. This occurs where the entropy profile becomes flat (moving inward), $r_\alpha \simeq 3 - 30$ kpc (Donahue et al. 2006; Cavagnolo et al. 2009). The free fall time from these regions is $\tau_{ff} \sim 10^7 - 10^8$ yr. The duty cycle might take somewhat longer. We attribute the time intervals between major AGN eruptions to the time it takes unstable clumps in large numbers to fall from these regions onto the SMBH.

Soker (2008) considered both the duty cycle and the radiative cooling time $\tau_{\rm cool}(12$ kpc$) < 8.5 \times 10^8$ yr $\equiv \tau_{\rm s}$ condition for high star formation rate in the frame of the cold feedback mechanism. Soker (2008) proposed the criterion that the feedback cycle period must be longer than the radiative cooling time of dense blobs for large quantities of gas to cool to low temperature. It is possible that the two conditions are required for star formation: that cold blobs in large number are unstable and cool to low temperature, and that the AGN heating duty cycle is longer than the cooling time.

3. SMBH MASS ACCRETION RATE

As usually done, we take the power in the jets to be

$$\dot{E}_{\rm jets} = \eta_j \dot{M}_{\rm acc} c^2. \tag{8}$$

We take the energy of the jets to be equal to the energy in bubble pairs of clusters. The cavity power is calculated assuming $4pV$ of energy per cavity, and the buoyancy timescale $t_{\rm b}$ for its formation. The energy and power of bubbles are taken from the list compiled by McNamara et al. (2010), with complementary material from Birzan et al. (2004) and Rafferty et al. (2006). The power of the jets is listed in the fifth column of Table 1. The clusters listed in Table 1 are those that we could find both entropy profile and jet (bubble; cavity) power in the literature. On the one hand this is the minimum energy, as some of the jets' energy goes to excite shocks and sound waves. On the other hand, we think the bubble filling is mainly non-relativistic, such that their energy should be $(5/2PV)$. Over all, the usage of $\dot{E}_{\rm jets} = P_{\rm cav} = 4pV/t_{\rm b}$ for the power of cavities is adequate for the present purpose. However, for the reasons listed above we think that the uncertainties in the power of jets are much larger than the uncertainties listed by McNamara et al. (2010). In the present Letter we do not include the uncertainties in the analysis, which is equal to assuming an equal (large) uncertainties to all points.

The entropy profiles, as well as some other cluster properties are taken from the catalog compiled by Cavagnolo et al. (2009). From the entropy profile we find the radius r_α, listed in the second column of Table 1, defined to be the radius where $\alpha = 0.5$ (equation 6). Inward to r_α the

entropy profile is flat. We also define the gas mass parameter

$$M_g \equiv \frac{4\pi}{3}\rho(r_\alpha)r_\alpha^3, \tag{9}$$

listed in the third column of Table 1. We use this parameter rather than the total gas mass inside r_α because in many cases the large bubbles near the center distort the density profile, and we are after a simple relation. We also list values of $\chi(r_\alpha)$ for $a = 0.01r$ and $gr_\alpha = (600 \text{ km s}^{-1})^2$ in the fourth column of Table 1.

We could not find a simple correlation between the jet power and χ, nor with the cooling time τ_{cool}, and nor with M_g/τ_{cool}. A short cooling time of $\tau_{\text{cool}} \lesssim 10^9$ yr at $r \simeq 10$ kpc is a condition for high star formation rate (Rafferty et al. 2008). However, once this condition is met it is not clear if the cooling time directly determines the mass accretion rate onto the SMBH.

In the cold feedback mechanism, the entropy profile seems to be a more fundamental parameter for mass accretion rate onto the SMBH, once a short cooling time is established. It was already found that high star formation rate and high $H\alpha$ luminosity require that the entropy floor in the cluster be $K_0 = kTn^{-2/3} \lesssim 30$ keVcm^2 (Voit et al. 2008). We look for a correlation rather than a limit. In Fig. 2 we plot the jets (cavity pair) power versus the size of the flat entropy region r_α (upper panel), and the gas mass parameter M_g (middle panel). A correlation, albeit not very strong, is clearly seen in all panels of Fig. 2. We look for the simplest correlation in the logarithmic plot, namely, a linear one. The correlations we find are

$$\log P_{\text{cav}}(\text{erg s}^{-1}) \simeq 1.65 \log \text{r}_\alpha(\text{kpc}) + 42.6, \tag{10}$$

with Pearson R coefficient of $R^2 = 0.67$, and

$$\log P_{\text{cav}}(\text{erg s}^{-1}) \simeq 0.58 \log \text{M}_g(\text{M}_\odot) + 38.5, \tag{11}$$

with $R^2 = 0.56$. Although these are not tight correlations, when the large scatter that is expected from the temporarily variations in the AGN power and its influence on the ICM is considered, these correlations have a merit.

Two comments are in place here. First, M_g strongly depends on r_α, $M_g \propto r_\alpha^3$, hence the two correlations are not independent of each other. Second, because of the large scatter and small number of objects, we did not perform any deeper statistical analysis. We only point to the existence of a correlation, and the potential of using it to estimate an average, over time and many clusters, SMBH mass accretion rate. In a forthcoming more detailed study we will try to incorporate elliptical galaxies to the correltion.

With the aid of equation (8), we cast the desired phenomenological formulae for the accretion rate on the SMBH in the form

$$\dot{M}_{\text{acc}} \simeq 0.03 \left(\frac{r_\alpha}{10 \text{ kpc}}\right)^{1.7} \left(\frac{\eta_j}{0.1}\right)^{-1} M_\odot \text{ yr}^{-1}, \tag{12}$$

Table 1: DATA ON CLUSTERS

Cluster	r_α	$M_g(r_\alpha)$	χ	P_{cav}	M_{mol}	K_0
	(kpc)	$(10^8 M_\odot)$		$(10^{42}$ erg s$^{-1})$	$(10^8 M_\odot)$	(keV cm^2)
A478	6.3	30	1.32	100	25^a	7.8
A1795	15.1	190	1.11	160	55^b	19
Perseus	20.8	500	2.78	150	350^c	19.4
A2199	6.2	12	0.24	270	2.7^d	13.3
A2052	7.4	5.9	0.11	150		9.5
A4059	3.0	1.7	0.19	96		7.1
Cygnus A	15.3	150	0.52	3900	15^d	23.6
A2597	12.2	110	1.86	67	45^a	10.6
Hydra A	11.6	77	0.83	2000	11^a	13.3
Centaurus	1.2	0.27	0.89	7.4		2.2
RBS797	25.2	1180	2.77	1200		20.9
2A 0335+096	8.9	50	3.19	24		7.1
A133	14.6	83	0.71	620		17.3
A262	5.1	3.4	0.14	9.7	9.30^d	10.6
M87	1.8	0.55	0.20	6.0	0.08^e	3.5
HCG62	2.7	0.99	0.92	3.90		3.4
MKW3S	18.5	130	0.35	410	5.4^d	23.9

Notes: The meanings of the quantities are as follows. r_α is the radius inward to which the entropy profile is flat, i.e., $\alpha < 0.5$. The entropy profiles and entropy floor K_0 are from Cavagnolo et al. (2009); The gas mass parameter $M_g(r_\alpha)$ is defined in equation (9); χ is according to equation (4); The power of the cavity pair, P_{cav}, is calculated by dividing the cavity pair energy, $4PV$, by the buoyant time, and taken from McNamara et al. (2010) and Rafferty et al. (2006). The molecular mass M_{mol} sources: (a) Edge (2001); (b) Salomé & Combes 2004; (c) Salomé et al. (2006); (d) Salomé & Combes (2003); (e) Tan et al. (2008).

and

$$\dot{M}_{\rm acc} \simeq 0.04 \left(\frac{M_g}{10^{10} M_\odot} \right)^{0.6} \left(\frac{\eta_j}{0.1} \right)^{-1} M_\odot \ {\rm yr}^{-1}. \tag{13}$$

Considering the large uncertainties in the physical parameters and the large scatter in the graphs, there is no point to give the numerical values in the above expressions to a higher accuracy.

The accretion rate does not increase as fast as the gas mass parameter M_g, because as we move to larger distances from the center the cooling time increases, and the gas supply becomes less efficient. However, equations (12) and (13) support the cold feedback mechanism in suggesting that mass accreted onto the central SMBH is drained from an extended region, particularly from where the entropy profile is flat.

McNamara et al. (2010) find no correlation between the molecular mass in clusters and the cavity power. We analyzed the 10 clusters that are in our sample and have molecular mass in McNamara et al. (2010) (taken from Edge 2001; Salomé & Combes 2003; Salomé & Combes 2004; Salomé et al. 2006; Tan et al. 2008). We confirmed their finding that the cavity power has no correlation with the molecular mass (we get a Pearson R coefficient of $R^2 = 0.13$). We do find a convincing correlation between the molecular mass $M_{\rm mol}$ and the entropy profile quantities r_α and M_g, as presented in Fig. 3. We again look for a simple linear relation in the log-log plots, and find

$$\log M_{\rm mol}(M_\odot) = 2.4 \log r_\alpha({\rm kpc}) + 6.8, \tag{14}$$

with Pearson R coefficient of $R^2 = 0.65$, and

$$\log M_{\rm mol}(M_\odot) = 0.89 \log M_g(M_\odot) + 0.50, \tag{15}$$

with $R^2 = 0.71$.

The above finding is very interesting. We find correlations of the entropy profile properties with both the cavity power and molecular mass. However, there is no correlation between the molecular mass and the cavity power. This shows two things. (1) The situation is not simple. There is a large scatter probably because the AGN activity substantially varies with time (Nipoti & Binney 2005). (2) The entropy profile seems to be the basic quantity determining the cooling of gas, both to form cold reservoir and to feed the SMBH.

We also correlate $P_{\rm cav}$ and $M_{\rm mol}$ with the entropy floor K_0 (from Cavagnolo et al. 2009), which is the value of the entropy in the inner flat region. The correlation with the molecular mass is poor (lower panel of Fig. 3). As shown in the lower panels of Fig. 2, the jets' (cavity) power clearly increases with the entropy floor. The linear fitting gives

$$\log P_{\rm cav}({\rm erg \ s}^{-1}) = 2.3 \log {\rm K}_0({\rm keV \ cm}^2) + 41.7, \tag{16}$$

with $R^2 = 0.67$. This behavior is *opposite* to what one would expect from a naive cooling interpretation. A naive expectation is that for a lower entropy the cooling is more efficient. However, a higher entropy floor goes along with a more extended (larger r_α) region; we find an almost proportionality

relation of $K_0(\text{keV cm}^2) \simeq 1.1\text{r}_\alpha(\text{kpc})$. We find that the cavity power (and possibly molecular mass) increases with the size of the flat entropy region. This is expected in the cold feedback mechanism (section 2), as long as the cooling time and the entropy floor are below their respective thresholds of $\tau_{\text{cool}}(12 \text{ kpc}) < 8.5 \times 10^8$ yr (Rafferty et al. 2008) and $K_0 = kTn^{-2/3} \lesssim 30$ keVcm^2 (Voit et al. 2008), respectively.

4. SUMMARY

Our main finding is the correlation of the jet power that went to inflate the bubble P_{cav}, with the size of the flat entropy region r_α (Fig. 2). (By flat profile we refer to a moderate profile with $\alpha < 0.5$.) The positive correlation between P_{cav} and properties of the flat entropy region in the inner regions of clusters is expected in the cold feedback mechanism. However, at this point the cold feedback mechanism does not give the form of the correlation. We have tried the simplest correlation in the log-log plot, and derived equations (10), (12). The correlation with the gas mass parameter defined in equation (9) is given in equations (11), (13).

There is a slight possibility that the correlation arises from an underlying effect that is not related to the feedback process. For example, a larger flat entropy region will cause jets to deposit more of their energy in the inner region and inflate large bubbles. However, the positive correlation of r_α with the molecular gas (Fig. 3), despite that the molecular gas does not correlate with the jet power, bring us to reject this possibility. Further support to this rejection is the positive correlation with the value of the entropy floor (the flat part at the center), as discussed in the last paragraph of section 3. We rather attribute a fundamental role to the flat entropy profile in the inner region in determining the cooling of the hot gas: The larger the flat entropy region is, the larger is the clumps' draining volume.

The relations (12) and (13) derived here, and a similar one that can be derived from equation (16), can be used for an estimate of the average mass accretion rate onto the SMBH. They should replace the Bondi accretion that does not fit accretion onto the SMBH in the center of clusters of galaxies (Soker 2006; Soker et al. 2009; Pizzolato & Soker 2010; McNamara et al. 2010).

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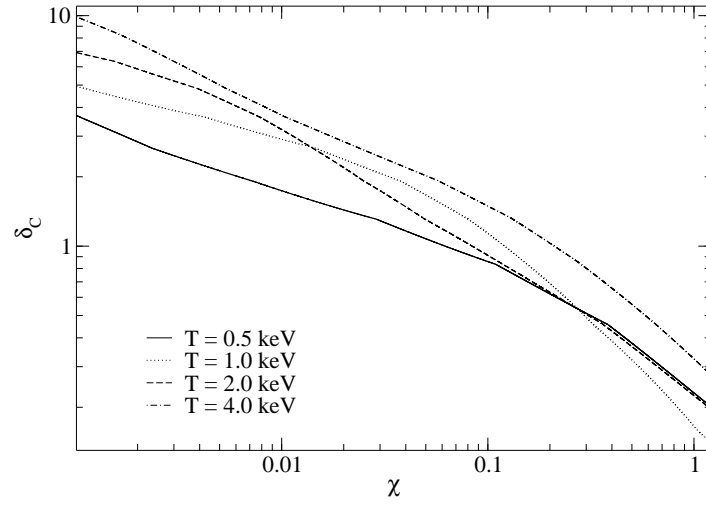Wise, M. W., McNamara, B. R., Nulsen, P. E. J., Houck, J. C., &David, L. P. 2007, ApJ, 659, 1153

Fig. 1.— Plot of the critical overdensity δ_C, implicitly defined by Equation 2 as a function of the parameter χ (Equation 2) for four values of the ambient temperature: $T = 0.5$ keV (solid line), $T = 1.0$ keV (dotted line), $T = 2.0$ keV (dashed line) and $T = 4.0$ keV (dot-dashed line).
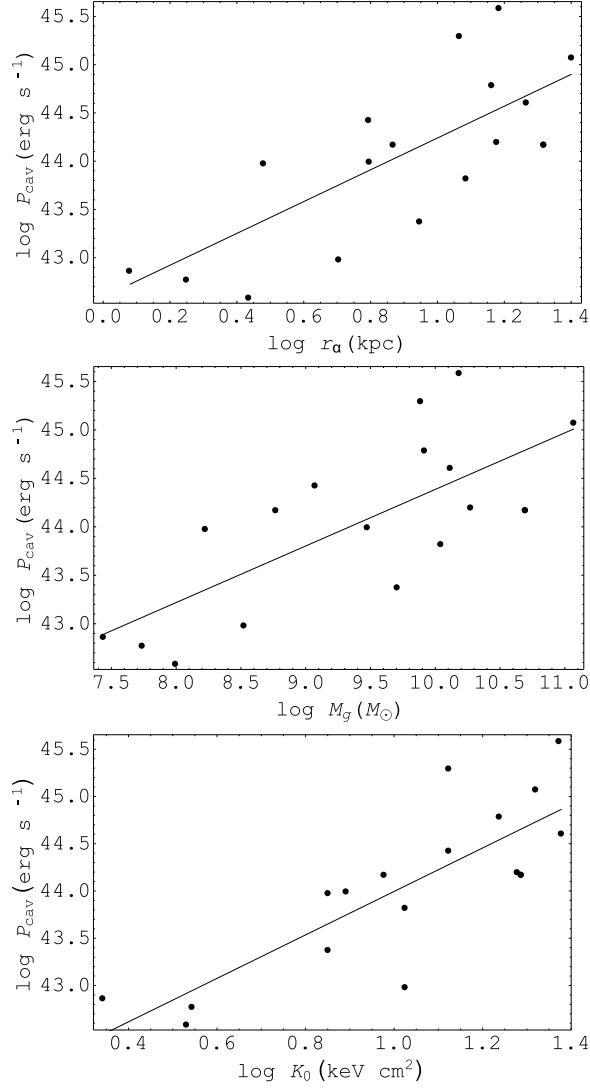
Fig. 2.— The cavity power (see Table 1) versus the size of the flat entropy region r_α (upper panel), the gas mass parameter M_g as given in equation (9; middle panel), and the entropy floor K_0 (lower panel).
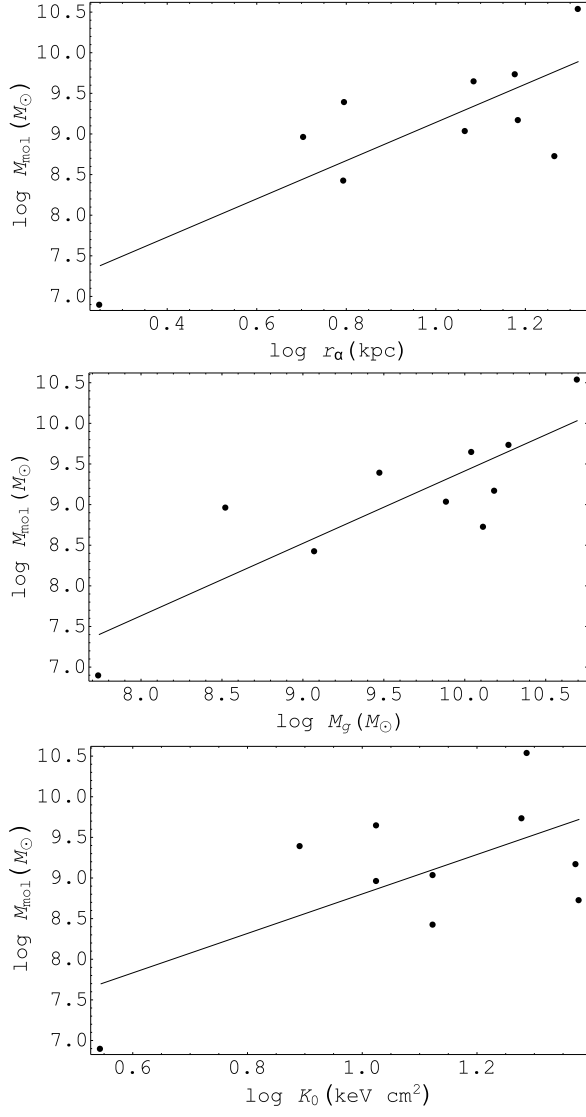
Fig. 3.— The molecular mass versus r_α (upper panel) and versus M_g (middle panel). For sources of data see Table 1.